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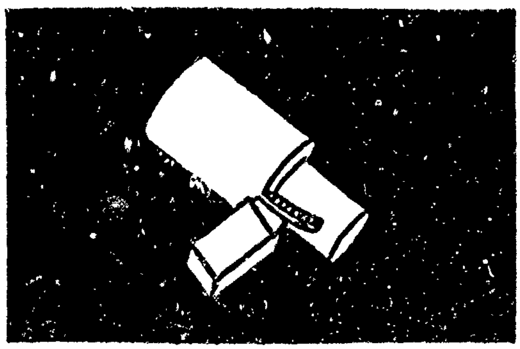

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Evaluation of Water-Base Cutting Fluids

by

M. C. Shaw
and
P. A. Smith

Machine Tool Division

Mechanical Engineering Department

Massachusetts Institute of Technology

10 APRIL 1961

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Evaluation of Water-Base Cutting Fluids

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M. C. Shaw[1] and P. A. Smith[2]

[1]Professor Mechanical Engineering, M.I.T., Cambridge, Mass.

[2]Associate Professor of Mechanical Engineering, M.I.T., Cambridge, Mass.

Abstract

Tool-life characteristics are discussed with regard to alloy-type and tool-life criteria. Relatively free machining steels are found to differ from alloy steels in that their constant wear-land Taylor curves are parallel to the total destruction. A tool life based on total destruction and one based on a constant given wear land appear to be justified, and rules for determining when each criterion should be applied are given. A generalized Taylor plot for tool life is presented, which also contains cost-optimum information.

A quantity is derived which is proportional to the optimum cost per part when a group of cutting fluids is tested. The best cutting fluid is the one for which this quantity is a minimum. It is found that in different speed ranges different fluids of a group are most effective. It is suggested that two types of water-base cutting fluids be recognized; one for use at high speeds (i.e., 500 fpm and above) which is primarily a coolant-like water, and one used at lower speeds where lubrication action is of importance. A simple bench test for rating the high-speed type of fluid is described, and representative results are considered. Methods of specifying satisfactory water-base cutting fluids are discussed briefly.

Introduction

In recent years a large number of new metal-cutting fluids have appeared on the market and it is an ever more difficult question to decide when one fluid is more advantageous than another. The many fluids available may be divided into two general classes—oil-base fluids and water-base fluids. The oil-base fluids are generally acknowledged to be the best boundary lubricants, while the water-base fluids are capable of the greatest cooling action. At low cutting speeds the production of good finish is the chief problem, and boundary lubrication of the tool-chip interface is of major importance; whereas, at high cutting speeds tool life is more important and cooling the cutting tool becomes more necessary.

The objective of this investigation is to study the performance of a variety of water-base cutting fluids and to attempt to device methods of assessing their relative values.

In the past, most tool-life studies have been performed on steels that are easy to machine, inasmuch as such steels are used in large volume, principally in automatic-screw machines. Much less attention has been given to alloy steels, and it was decided early in this investigation that the influence of cutting fluids on alloy steels should receive particular attention. It was also thought advisable to employ a multiple-edge disposable type of carbide tool, inasmuch as such tools are being used in ever increasing volume.

The question of whether tool life should be measured by total destruction or when a certain value of wear land has been reached is one that has been much debated. It was, therefore, decided to look into this matter in connection with this study. However, it was recognised at the outset that tool life is only of importance when it influences the manufacturing cost per part, and should not be considered to be the principal objective. It was, therefore, evident that the ultimate method of deciding between two fluids should be based upon their relative influence on the cost per part. Need was felt for answers to such questions as: is the cost of a cutting fluid of importance if it really provides superior performance? and how much additional cost for a cutting fluid is justified in a given instance? An attempt to give general answers to these questions will be made in this report.

Tool Life of AISI 4340 Steel

Since this investigation was confined to a comparison of water-base cutting fluids, and since such fluids are used principally as coolants at high cutting speeds in order to increase tool life, it was decided to first investigate the influence of cutting fluids upon tool life. After a number of preliminary tests a disposable-type carbide tool was found which gave very good results, and this tool was adopted for this study. The characteristics of this tool and the cutting conditions used follow:

Carbide Type: Steel cutting grade C-5.

Carbide Size: 3/8" x 3/8" x 1-1/2" rectangular parallelopiped.

Tool Angles:

- Back-Rake Angle, -7°
- Side-Rake Angle, -7°
- End-Relief Angle, 7°
- Side-Relief Angle, 7°
- End-Cutting-Edge Angle, 15°
- Side-Cutting-Edge Angle, 15°
- Nose-Radius, 1/32 inch

Feed, 0.0104 ipr

Depth of cut, 0.100 inch

Cutting speed, variable

Each tool insert had eight cutting edges and when these had been used the carbide insert was discarded.

The work material used was annealed AISI 4340 steel (brinell hardness [illegible]35).

It was decided to thoroughly investigate the nature of the tool-life cutting speed curve for AISI 4340 steel using a given cutting fluid before running tests on a variety of fluids. For this initial study it was decided to use tap water without any additive, since this provided a convenient constant source of material that would not change in concentration with time and would not become contaminated, since it was not recirculated. It was also thought best to run all tools to total destruction so that a comparison could be made between curves of constant wear land and the curve of total destruction. This required that a large amount of material be cut, and some tests involved as many as 16 hours of cutting time.

The water was applied at the rate of 1-1/2 gal/min at a temperature of 60°F and was directed down onto the tool face and the back surface of the chip. The lathe used in these tests was equipped with a D.C. motor so that the cutting speed could be held constant as the diameter of the work changed. The bars used were initially seven inches in diameter and 24 inches long, and were discarded when the diameter reached 2-1/2 inches. The wear land on the clearance face of the tool was measured after each pass across the work using a tool maker's microscope. In the data presented the wear land (w) is shown plotted against the helical distance (L) on the work passing the cutting edge in feet. The point of total destruction is marked by a vertical line on all plots.

Several changes were observed to occur in the tool under different operating conditions: (see diagramatic sketches in Fig. 1)

1. At cutting speeds above 600 fpm tool life was very short, and there was evidence that the temperatures pertaining at the tool point were too high. The cutting edge was observed to flow plastically under the cutting pressure and changed its shape as shown in Fig. 1b.

2. A crater was found to develop on the top surface of the tool, particularly in the speed range from 300 to 600 fpm. This crater first appeared a short distance from the cutting edge and then grew in both directions (Fig. 1c). Usually when the crater just reached the cutting edge the tool would fail completely.

3. A wear land was found to develop on the principal ~~clearance~~ clearance face of the tool (Fig. 1d) at all speeds. This land (w) was convenient to measure and was recorded after each pass in all tests.

4. Chipping of the cutting edge was experienced in early tests, primarily at the end of the cut as the tool broke through the free surface. This difficulty was not eliminated by providing a taper at the

end of the bar to enable the tool to leave the work in a gradual manner. It was found, however, that this type of chipping was eliminated by disengaging the feed at the end of the cut and before the tool broke through (Fig. 1a).

5. At low cutting speeds (below about 300 fpm) there was evidence that a built-up edge (BUE) was present at the tool tip (Fig. 1e). This evidence was in the form of a rather sudden increase in workpiece roughness with decrease in speed and a decreased tendency for the crater to grow toward the cutting edge at this same speed. When the BUE was present the crater did not reach the cutting edge by growing toward it, as at higher speeds, but rather by the wear land approaching the crater.

Wear land curves for AISI 4340 steel cut using water as the cutting fluid are given in Fig. 2 and the corresponding Taylor Plots are given in Fig. 3. The appearance of the wear land as it grew was as shown in Fig. 4a at all speeds except the very lowest (50 fpm). The particular wear pattern shown in Fig. 4a is for a speed of 400 fpm. The wear land was essentially constant across the cutting edge except for the region at the outer edge of the chip (region C) where the wear land was somewhat greater. At a speed of 50 fpm (Fig. 4b) the wear land at the outer edge of the chip was even more pronounced and there was additional wear in region A at the tool tip. The value of wear land that was plotted was that for region B in all cases except for 50 fpm. Since the additional wear present at region C is not thought to be important with regard to tool performance and inasmuch as it is so far removed from the cutting edge, this detail was ignored in the analysis of the wear data. The curves of Fig. 3 represent a very complex picture compared with the results generally obtained using a free machining steel. The following observations may be made after studying Fig. 2 and 3:

1. The total destruction curve is a straight line only for speeds between that where the BUE disappears (300 fpm) and that where the tool is overheated and flows plastically (600 fpm). The presence of the BUE causes the total destruction curve to fall below the linear curve for the 300-500 speed range and to eventually undergo a complete

reversal in the region where the BUE is very large. Thus, at speeds below about 100 fpm the tool life (total destruction) is actually increased by increasing the cutting speed.

2. The lines of constant wear land are very complex. At speeds above 300 fpm, where there is no BUE, the constant wear land curves have a slope of approximately 45°, which means that the size of the wear land depends only on the helical distance cut (L), and is independent of the speed from 300 to 500 fpm (see Fig. 2).

3. When the BUE first appears the wear land curves rise, indicating that in the region from 250 to 300 fpm the presence of the small BUE present is beneficial to the rate of development of the wear land.

4. As the BUE gets larger and as the speed is further reduced, it has a detrimental effect upon the rate of development of the wear land. In Fig. 2 the wear land is seen to develop at a less rapid rate at 250 fpm than at 200 fpm.

5. The very low value of tool life (total destruction due to crater formation) at 50 fpm is undoubtedly due to the large BUE present at this speed and the consequent large size of the individual wear particles that are pulled from the tool. As will be shown later when finish considered, the BUE is a maximum at 50 fpm for this work-tool combination. We should then expect the tool-life curve to rise at speeds above 50 fpm as shown by the dotted curves. If this is the case, then 50 fpm would correspond to a "Valley of Death," which is a picturesque term that has been used in the literature to describe a speed for which tool life improves upon leaving this speed in either direction. It should be noted that for this alloy steel, tool life will continue to increase with speed to a speed of 250 fpm if a wear land of from .040 to .030 inch is taken as the criterion for tool life. However, it is also important to note that the "Valley of Death" discussed here is one which occurs in the region of large BUE (usually from 0 to 200 fpm), whereas most other discussions of this phenomenon are concerned with very high speeds. It appears that when cutting without a BUE tool life (no matter how defined) will always decrease with an increase of cutting speed, and

under such conditions a "Valley of Death" will not be observed.

Other Steels

In contrast to the complex picture of Fig. 3 for AISI 4340 steel we have the relatively simple case for softer steels. In Fig. 5, 6, and 7 are shown results for AISI 1020 steel. Representative wear-land patterns are shown in Fig. 7. In all cases, the wear-land values for region B were plotted. In Fig. 8 and 9 data are shown for AISI C1117 steel. For both the AISI 1020 and C1117 steels, the lines of constant wear land and total destruction were found to be exactly parallel. This may be taken to mean that for the softer unalloyed steels the crater plays a relatively unimportant role and total destruction occurs when the wear land reaches a certain critical value. The mode of tool failure is believed to be associated with a softening of the work material along the wear land and a sudden increase in the contact area and number of welds occurring per unit time when the wear land and hence the wear-land temperature reaches a particular value. This mechanism has been described in detail in a previous paper (1). In contrast to the soft unalloyed steels, AISI 4340 steel is stronger and more refactory. Its greater strength will increase the pressure between chip and tool and increase the tendency for a crater to form, while its greater tendency to retain its hardness at higher temperatures will prevent a wear-land failure from occurring. Thus, in the case of AISI 4340 steel we find the Taylor curve of total destruction to make a considerable angle with the curves of constant wear land which clearly indicates that in this case total destruction results from the crater and not from the wear land. This material is in fact so refractory that the rate of development of wear land (w vs L) is completely independent of cutting speed to 500 fpm if no BUE is present.

Weber (2) has presented tool-life results for a material (German equivalent of AISI 1068) that is intermediate between the AISI 1020 and AISI 4340 steels. Taylor plots of Weber's data for a HSS tool and a carbide tool are given in Fig. 10. Here it is evident that the lines of constant wear land intersect the lines of total destruction at an angle, but this angle is not as great as in the case of the AISI 4340 steel. The lines of constant R will be referred to later. Weber noted that total destruction occurred at an approximately constant ratio of crater depth to crater half length ($\frac{K_T}{K_M}$) and lines for constant values of this ratio are also shown in Fig. 10. Tool failure is seen to occur when $\frac{K_T}{K_M}$ reaches a value of between about .4 and .6.

From the foregoing discussion it is evident that the tool-wear characteristics of a highly alloyed steel are far more complex then those for a relatively free machining steel. The free machining steel will have constant wear land and total destruction curves that are parallel. On the contrary a highly alloyed steel will have a complex family of wear-land curves that are parallel to each other only in the absence of BUE. In addition, the total destruction curve for such a steel will make a considerable angle with the wear-land plots.

Machining Cost

Returning now to the AISI 4340 steel the question arises as to what speed range should be used in making a comparison of different cutting fluids. Clearly such a comparison should be made at the speed corresponding to minimum cost per part and hence, machining costs will be considered next.

Usually a straight Taylor plot of tool life (T) in minutes vs cutting speed (V) in fpm will be obtained at speeds above which the BUE has disappeared. The equation of this curve is

$$VT^n = C \tag{1}$$

where n and C are constants depending upon cutting conditions.

If cutting is done at high speed the machine and labor cost will be low, but the tool cost will be high. The opposite is true if cutting is done at low speed. There is an optimum cutting speed for any machining operation where the machining cost per part is a minimum.

The costs to be included in such an analysis are:

1. Direct machine and labor costs (xT_p) where x is the value of the machine and operator with overhead in cents per minute and T_p is the machining time per part in minutes

$$T_p = \frac{\pi d \ell_a}{12tV} = \frac{L_p}{V} \tag{2}$$

where d is work diameter, in.

ℓ_a is axial length to be machined, in.

t is the feed, ipr

V is cutting speed, fpm

L_p is the helical distance tool travels in machining a part in feet.

2. Tool changing cost per part ($xT_d\frac{T_p}{T}$) where T_d is the down time to change tools in minutes and (T) is the tool life in minutes.

3. Tool cost per part ($y\frac{T_p}{T}$) where y is the mean value of a single cutting edge.

The machining cost per part then becomes:

$$\not{c} = xT_p + xT_d\frac{T_p}{T} + y\frac{T_p}{T} \tag{3}$$

For optimum performance we should like the machining cost per part to be a minimum and analysis shows that this occurs when the tool life has the value

$$T^* = \frac{xT_d + y}{x}\left(\frac{1}{n} - 1\right) = R\left(\frac{1}{n} - 1\right) \tag{4}$$

where n is the value of the exponent of equation (1) and hence, the inverse slope of the Taylor plot using log-log coordinates. It follows from equations (1) and (4) that the corresponding cost optimum speed is

$$V^* = \frac{C}{(T^*)^n} \tag{5}$$

and the minimum cost per part is

$$\not{c}^* = \frac{xT_p^*}{1-n} \qquad (6)$$

The lines of constant wear land for AISI 4340 steel (Fig. 3) have a value of $n = 1$ for the speed range extending from 300 fpm to the line of total destruction. From equation (4) T^* is seen to be 0 which means that minimum cost per part corresponds to an infinite speed. What this in turn means practically is that for this material minimum cost per part will correspond to some point on the total destination curve rather than on a curve of constant wear land.

The value of n for the total destruction curve of Fig. 3 is 0.27 and hence, from equation (4) the optimum tool life for minimum cost will be

$$T^* = 2.7R \qquad (7)$$

Lines of constant R are shown in Fig. 3 and the points of intersection of these lines and the curve of total tool destruction will give the optimum cutting speed (V^*) corresponding to minimum cost per part in any case. Lines of constant R are also given in Fig. 6, 9, and 10.

A specific example may be considered to illustrate the use of the constant R curves. Let us assume the following values of cost for the tool of Fig. 2 and 3.

x = value of machine with labor and overhead = 10 ¢/min ($6 per hour)

T_d = time to change and adjust tool = 5 min.

y = value of single cutting edge = (in case of tool of Fig. 3) $\frac{520}{8} = 65$¢ if the tool is not reground and possible less if reground.

Hence,

$$R = \frac{xT_d + y}{x} = \frac{10(5)+65}{10} = 11.5.$$

From equation (7) the x optimum tool life (T^*) is 31 minutes and from Fig. (4) the speed to give minimum cost per part is seen to be 570 fpm at the point where the R = 11.5 line crosses the line of total tool destruction.

In arriving at this value we have assumed that it is permissible to have a wear land as large as that pertaining at the total destruction condition (approximately .030 inch). This will usually be the case in rough turning operations. However, in certain instances it is not permissible to exceed a certain wear land for reasons of finish, vibration, magnitude of machining forces or limitations of power. If in the present example the largest permissible wear land was 0.040 inch, due to the finish becoming too poor for larger values, then the optimum operating point would be either

1. where the R curve for the w = 0.040 inch tool-life line crosses the w = 0.040 inch line. The corresponding value of V may be designated V^*; or
2. where the w = 0.040 inch line crosses the line of total destruction. The value of V in this case may be designated V_1^*.

Since the intersection corresponding to (1) lies to the right of the total destruction line in the case of AISI 1340 steel, item (2) above is the one which obtains in the present case and the optimum cutting speed for a maximum permissible wear land of 0.040 inch would be (V_1^*) = 525 fpm.

It would thus appear to have a logical answer to the question concerning whether tools should be used to just short of a given wear land or to just short of total destruction. In some cases the one criterion should be used while in other cases the other criterion should be used.

Cutting Fluid Tests

Tool-life results for several water-base cutting fluids are given in Fig. 11 for conditions identical to those of Fig. 3. In these tests the data have been confined to the practical turning region where BUE is negligible. Both lines of constant wear land and total destruction are included. In each case lines of constant R have also been given and the value of R corresponding to the tool used (R = 11.5 min) is shown by a dotted line.

Two examples will be used to compare the performance of these fluids. First, it will be assumed that we are interested in a roughing operation for which it is permissible to use tools to total destruction. The optimum cutting speed (V^*) and tool life (T^*) in this case corresponds to the point where R = 11.5 crosses the total destruction line for each fluid (Fig. 11). The values of T^*, V^* and n for each of the fluids tested are given in table 1.

Table 1

For Total Destruction (R=11.5)

Fluid	n	V_1^* rpm	T_1^* min.	$\frac{\not{c}^*}{xL_p}$	Relative Cost
Water, noncirculating 60°F	.27	570	31.0	.00240	.88
Water, Circulating 90°F	.32	610	24.5	.00241	.88
Cutting Fluid A, 2.5%	.22	500	40.8	.00256	.94
Cutting Fluid B, 2.5%	.23	515	38.5	.00252	.92
Cutting Fluid C, 2.5%	.32	610	24.5	.00241	.88
Cutting Fluid D, 2.5%	.23	510	38.5	.00255	.95
Dry Tool	.24	480	36.4	.00274	1.00

The minimum cost per part $\not{c}^*$ is given by equation (6) from which it is evident that (see Eq. 2)

$$\not{c}^{*} = (xL_p)\frac{1}{V^{*}(1-n)} \tag{8}$$

Since the quantity in parenthesis is constant for any operation, the optimum cost per part ($\not{c}^{*}$) will be proportional to $\left(\frac{1}{V^{*}(1-n)} = \frac{\not{c}^{*}}{xL_p}\right)$ for any given cutting fluid and values of this quantity are included in table 1. The values of relative cost given in the last column of table 1 are based on a cost per part in dry cutting of unity.

From this study it is evident that all water-base cutting fluids give better results than dry cutting. The poorest fluid showed a decrease in cost per part over dry cutting of about 6% while the best fluid showed a decrease in cost per part of 12% based on dry cutting. The fact that none of the commercial water-base cutting fluids was better than water indicates that the major role of the fluid in this speed range (500 to 600 fpm) is one of cooling. Water should be expected to be the best coolant and the performance of the water-base fluids should be expected to decrease from that of water as their tendency to form a thick oily deposit on metal surfaces increases. Such a thick oily film will tend to decrease the heat transfer coefficient between metal and fluid. The four water-base cutting fluids tested might be rated in the following order of decreasing effectiveness for use in the speed range 500-600 fpm:

Fluid	% Improvement Over Dry Cutting
C	12 (circulating water 12%)
B	8
D	7
A	6

A second comparison may be made for the case where a wear land of 0.040 inch cannot be exceeded for reasons of let us say surface finish. The best operating point in this case (V_1^{*} and T_1^{*}) will be the point where the w = .040 inch curve intersects the curve of total destruction. Such values of T_1^* and V_1^* are given in table 2.

Table 2

For Constant Wear Land
of 0.040 inch (R=11.5)

Fluid	V_1^* fpm	T_1^* min	$\frac{\not{c}_1^*}{xL_p}$	Relative Cost
Water, Noncirculating, 60°F	525	40	.00246	.87
Water, Circulating, 90°F	410	88	.00276	.97
Cutting Fluid A, 2.5%	460	60	.00259	.91
Cutting Fluid B, 2.5%	450	65	.00262	.92
Cutting Fluid C, 2.5%	420	80	.00272	.96
Cutting Fluid D, 2.5%	440	72	.00264	.93
Dry Tool, 2.5%	420	60	.00284	1.00

The equation which in this case corresponds to equation (8) may be readily shown to be

$$\not{c}_1^* = (xL_p)\frac{T_1^*+R}{T_1^*V_1^*} \qquad (9)$$

where the quantity in parenthesis is again a constant for any given operation. Hence, the minimum cost per part ($\not{c}_1^*$) with any cutting fluid will now be directly proportional to the quantity $\left(\frac{T_1^*+R}{T_1^*V_1^*} = \frac{\not{c}_1^*}{xL_p}\right)$ given in table 2 for a value of R of 11.5.

The optimum speed is now seen to range from 420 to 460 fpm, and for this speed range water and water-like fluids are the least effective. The relative rating of fluids for the 0.040 inch wear land condition are now as follows in decreasing order of effectiveness.

Fluid	% Improvement Over Dry Cutting
A	9
B	8
D	7
C	4 (circulating water=3%)

Apparently lubrication begins to be important in this speed range and the fluid (a) that was poorest at the high-speed range of 500-600 fpm (table 1), because of its interference with heat transfer, now appears to be the most effective fluid for the 420 to 460 fpm speed range. The range of effectiveness of the commercial fluids is still seen to be about 2 to 1 but the order of effectiveness is entirely changed.

Still another comparison of the effectiveness of these cutting fluids can be made for a case where the tooling is relatively expensive. Let us consider the specific case where tools are run to just short of total destruction and the value of R has been increased by a factor of four to a value of 46. The quantities of interest for this example are given in table 3.

Table 3

For Total Destruction (R=46)

Fluid	n	V_1^* fpm	T_1^* min	$\frac{\phi^*}{xL_p}$	Relative Cost
Water, Noncirculating, 60°F	.27	390	124	.00352	.92
Water, Circulating, 90°F	.32	390	98	.00376	.98
Cutting Fluid A, 2.5%	.22	370	163	.00346	.91
Cutting Fluid B, 2.5%	.23	375	154	.00347	.91
Cutting Fluid C, 2.5%	.32	390	98	.00377	.99
Cutting Fluid D, 2.5%	.23	370	154	.00351	.92
Dry Tool	.24	345	146	.00352	1.00

The optimum speed is now still lower, ranging from 345 to 390 fpm. The relative ratings of the fluids are as follows:

Fluid	% Improvement Over Dry Cutting
A	9
B	9
D	8
C	1 (circulating water—2%)

Now the water and water-like fluid (C) are seen to be not only the poorest fluids of the group but to be practically without effect.

The foregoing analysis of water-base cutting fluids has clearly shown that two distinct actions are present which are not completely compatible—a lubrication action and a cooling action. For the AISI 4340 steel-carbide-tool combination used in these experiments, cooling seems to be of negligible importance for speeds of 300 fpm and below, while lubrication assumes an increasing role of importance. On the other hand, at speeds of 600 fpm and above, only cooling seems to be beneficial and any lubricating properties a fluid may have appear to be detrimental. Of the fluids tested it would appear that fluids A and B have the best lubricating characteristics, while water and fluid C have about the same cooling characteristics. For cutting at speeds from 300 to 500 fpm fluids A or B should be used, but for speeds above 500 fpm fluid C would be distinctly better.

The best performance for each of the three cases considered in tables 1 to 3 are summarized in table 4. Here the optimum tool life is seen to go from 24 minutes to 60 minutes as the criterion of failure changes from total destruction to a wear land of 0.040 inch. The optimum life rises to 163 minutes when R is increased from 11.5 to 46. The decrease in cost in going from a wear land of 0.040 inch to total destruction is seen to be of the same order of magnitude as the decrease in cost associated with the use of a fluid. A very large difference in cost is seen to be associated with a change in R. As less expensive disposable carbide tools are developed we should expect V^* to increase and T^* to decrease to values as low as 20 minutes. For such tools water-type fluids should be more widely used at higher cutting speeds.

Table 4

Summary of Best Performance

Case	Fluid	T_l^* min	V_l^* fpm	$\frac{¢^*}{xL_p}$	Relative Cost	% Improvement over Dry
Total destruction, R=11.5	C	24	610	.00241	1.00	12
Wear land = 0.040 in., R = 11.5	A	60	460	.00259	1.07	9
Total destruction, R = 46	A	163	370	.00346	1.44	9

Cutting Fluid Cost

The quantity $(\frac{¢^*}{xL_p})$ is not only useful in deciding which fluid of a group is best, but it can also be used to determine how much we are justified in spending for a particular cutting fluid. This is most effectively illustrated by an example. Let us assume that a part is to be produced under the following conditions:

x = value of machine and labor = 10 ¢/min ($6 per hr.).

d = diameter of part = 2 in.

ℓ_a = axial length of part = 2 in.

t = feed = .010 ipr

The quantity in parenthesis in equation (8) is then

$$xL_p = \left(\frac{x\pi d\ell_a}{12t}\right) = \frac{(10)\pi(2)(2)}{12(.010)} = 1050$$

From table 1 the value of cutting fluid A to this operation (assuming tools are used to total destruction) is clearly

$$¢^*_{dry} - c^*_A = (1050)\left[\left(\frac{¢^*}{xL_p}\right)_{dry} - \left(\frac{¢^*}{xL_p}\right)_A\right]$$

$$= 0.19 \quad , ¢ \text{ per part.}$$

If this fluid is used as a 2-1/2% solution and the concentrate costs g ¢ per gallon then the cost of the solution will be (.025)g ¢/gallon. If N parts can be made per gallon of solution (including drag-out with chips, evaporation, replacement, etc.), then the cost of fluid per part will be $(\frac{.025g}{N})$ ¢. The use of cutting fluid A is justified on a cost basis if

$$¢^*_{dry} - c^*_A > \frac{.025g}{N}$$

In the above example fluid A costs $2.00 per gallon and hence, for the fluid to be justified on a cost basis

$$N > \frac{¢^*_{dry} - c^*_A}{(.025)(200)} = \frac{.19}{(.025)200} = .04$$

The number of parts that may be produced per gallon of solution will greatly exceed 0.04 and hence, it would appear that the fluid is certainly justified on a cost basis.

The optimum total cost per part including machining costs and fluid costs will be $(¢^* + \frac{cg}{N})$ in any particular case where c is the concentration of the active ingredient that is used. The fluid of a group for which this quantity is a minimum is the most economical one to use and hence, normally should be the one used if other conditions are equivalent. The cost of the fluid per part $(\frac{cg}{N})$ will normally be completely negligible compared with the machining cost per part and hence, <u>that fluid which gives the smallest machining cost per part is normally the most economical regardless of the cost of the fluid concentrate.</u> Thus, it is clear that if a particular fluid really does a superior job and the machining cost per part $(¢^*)$ is reduced any measurable amount by using it, this water-base fluid should be used regardless of whether the concentrate costs one, ten, or twenty dollars per gallon.

Free Machining Steels

Free machining steels have lines of total destruction and constant wear land which are parallel. The fluid giving the best performance with such a steel will always be the one for which $\left(\frac{\delta^*}{xL_p} = \frac{1}{V^*(1-n)}\right)$ is least where V^* is the speed corresponding to the point of intersection of the proper R value and the allowable wear land (or total destruction line). Equation (8) will apply in all cases for free machining or mild steels (such as AISI steels: B1112, C1213, C1117, 1018 or 1020) and whether we work to a constant wear land or to total destruction. As an example, consider Fig. 6 and a tool for which R is 40. If the tool is carried to total destruction $\left(\frac{1}{V^*(1-n)}\right)$ would be $\frac{1}{(1250)(1-.47)}$ or .00151. If, on the other hand, the tool had to be taken from service when a wear land of 0.0[illegible] inch was reached to meet other specifications, then $\frac{1}{V^*(1-n)}$ would be $\frac{1}{(520)(1-.47)}$ or .00364.

The value of the tool actually used to obtain the data for Fig. 6 had an R value of 11.5 (same tool as that used for Fig. 3). If we were to cut AISI 1020 with this tool under optimum conditions we would have the following values:

$$T^* = 11.5\left(\frac{1}{.47} - 1\right) = 12.5 \text{ min.}$$

$$V^* = 2600 \text{ fpm (from Fig. 6)}$$

$$\delta^*/xL_p = 0.000725.$$

If however, the particular lathe available could not turn the work at 2600 fpm, but the maximum speed was limited to 1000 fpm we would then have

$$V_1^* = 1000 \text{ fpm}$$

$$T_1^* = 70 \text{ min (intersection of } R=11.5 \text{ and total destruction line in Fig. 6)}$$

$$\delta_1^*/xL_p = \frac{T_1^*+R}{V_1^* T_1^*} = 0.001165$$

With $R = 11.5$ and $w = 0.02$ inch as the tool-life criterion we would have

$$T^* = 11.5(\frac{1}{.47}-1) = 12.5 \text{ min.}$$

$V^* = 950$fpm (intersection of $R = 11.5$ and $w = .02$ lines)

$$c^*/xL_p = 0.00198$$

The values in these several examples are summarized in table 5.

Table 5

Summary of AISI 1020 Examples

Life Criterion	R	T_1^* min.	V_1^* fpm	ϕ^*/xL_p	Relative Cost
Total destruction	11.5	12.5	2600	.000725	1.00
$V_{max} = 1000$	11.5	70	1000	.001165	1.61
$w = 0.02$ in.	11.5	12.5	950	.00198	2.73
Total destruction	50	45.2	1250	.00151	2.08
$w = 0.02$ in	40	45.2	520	.00364	5.02

It is evident from table 5 just how important it is on a cost basis to

1. operate with low values of R;
2. use tools to as close to total destruction as possible;
3. be able to operate at optimum speed even when such speeds are very high.

By comparing values of $(\frac{1}{V^*(1-n)} = \frac{\phi^*}{xL_p})$ for different cutting fluids when cutting a free machining steel we again have a convenient method of comparing the performance of these fluids on a cost basis.

Steels of Intermediate Hardness

The free-machining steels have been seen to give one type of Taylor plot (lines of constant wear land and total destruction parallel), while alloy steels such as AISI 4340 or greater alloy content give another (lines of constant wear land at 45° to line of total destruction). Still other steels of the type AISI, 1045, 1060, 1080, 4140, or 5120 will give Taylor plots intermediate between those for AISI 4340 and AISI 1020. For such steels equation (8) will always be applicable to tools carried to total destruction. For operation to a constant wear land, equation (8) will apply only when the intersection of the R line and the line of constant wear land lies to the left of the total destruction line. In such cases the value of n to be used corresponds to that of the wear land and not to the total destruction line. In those cases where the intersection of the R line and the constant wear-land curve lies to the right of the total-destruction line the treatment for a constant wear-land case should be as in the AISI 4340 examples previously presented (i.e., equation 9 should be used in place of equation 8).

Cooling Characteristics of Fluids

The results obtained with the AISI 4340 steel indicate that at speeds in excess of 500 fpm, where no BUE is present, cooling is the major function of the fluid. When speeds of the order of 1000 fpm are used, it appears that there is not even time for cooling, not to mention lubrication action. With AISI 1020 steel cut at 1000 fpm neither the fluid used nor its method of application was found to have any effect on tool life.

Thus, in the intermediate speed range (i.e., above BUE speeds and below speeds where there is not time for cooling) the cooling characteristics of the fluid are thought to be very important and it should be possible to measure the relative ability of different fluids to cool a hot body by a suitable bench test. In considering the times available for cooling a tool or workpiece, there appear to be two values which should be considered.

1. As the metal cut crosses the shear plane it is highly deformed and practically all of the deformation energy ends up as thermal energy which raises the temperature of the chip. Any heat that can be extracted from the back of the chip while it is in contact with the tool will help lower the equilibrium temperature of the tool. The time for this cooling

is very small, since the time of contact between chip and tool is very short. If we cut at 400 fpm the velocity of the chip will be about 200 fpm, the length of contact between chip and tool will usually be 0.040 inch or less and hence, the time available for cooling the chip will be about $\frac{(0.040)(60)}{(200)(12)} = 0.001$ sec.

2. The temperature of the metal approaching the shear plane will be lowered by heat transfer between the fluid stream and the bar. The time the fluid stream is in contact with the workpiece is relatively long and may be estimated by dividing the half diameter of the fluid stream by the product of the feed and the rpm of the bar. Thus, if we have a four-inch bar being cut with a 0.010 ipr feed at 400 fpm, the rotative speed will be of the order of 100 rpm, and the time of direct contact between fluid and work up to the shear plane will be $\frac{.5(60)}{(100)(.01)}$ or 30 seconds, if the fluid stream is assumed to be one inch in diameter and centered over the cutting edge of the tool.

The temperature difference associated with the second time is not great and the heat removed from the bar is a relatively long distance from the cutting edge. Furthermore, the cooling capacity of all water-base cutting fluids is about the same when relatively long cooling times are involved. The chip itself will have a temperature that is at least 600°F and heat extracted during time (1) is closely located to the cutting edge of the tool. It is, therefore, thought that the cooling that occurs during time (1) is the most significant with regard to the influence that water-base fluids have upon high-speed tool life. Apparatus was, therefore, constructed to study the short-time cooling characteristics of fluids.

A heater was built consisting of a steel plate, heating coils, and insulating fire brick. The plate was 1/4 inch thick and the heater consisted of resistance wire wound on mica. Temperature of the plate was altered by means of a variac. An iron-constantan thermocouple was brazed to the face of the steel plate at a point 0.01 inch below the surface, and the cold junction was at room temperature. The thermocouple output was fed into an oscilloscope and a 35-mm camera was used to photograph the resulting traces.

After the plate temperature had reached equilibrium the fluid was directed onto the thermocouple junction and the temperature trace recorded for the first few milliseconds after impingement. A representative trace for a stream of water is shown in Fig. 12.

Results of a number of tests obtained using water and different water-base fluids are shown in Fig. 13. Here it is seen

1. that water is the best coolant;
2. that fluids A, B, and C are not quite as good as water, but approximately the same as each other (fluid C is the best coolant of this group and most like water);
3. that the cooling capacity of an air jet is very poor relative to water or water-base fluids.
4. that fluid E, which is the old oil in water emulsion, has poor cooling characteristics due to its oily nature and the resulting low-heat transfer coefficient.

All of these observations are as might be expected from table 1, and this similarity tends to further indicate that the fluid action that improves tool life in the vicinity of 500 fpm is primarily one of cooling.

This cooling test in itself is not sufficient to give the complete picture for cutting fluids since it says nothing regarding the boundary lubrication action that becomes important at speeds below 500 fpm. However, it does seem to correlate well with tool-life results for speeds in the vicinity of 500 fpm.

Surface Finish

Tests of the surface finish produced using different water-base cutting fluids failed to reveal any significant difference. In fact, a dry tool gave finish results that were as good as those obtained with the fluids at speeds above 150 fpm. These tests were all run in the absence of feed marks by interchanging feed and depth of cut and turning the tool through 90°. This technique provides a cut that is exactly equivalent to the conventional one, but the surface which results has feed marks that are 0.100 inch apart instead of the usual feed spacing of 0.010 inch.

The variation of surface finish was found to be strongly dependent on cutting speed for speeds below 150 fpm, a maximum roughness was found at about 50 fpm. Below this speed the roughness was found to decrease just as in going to speeds above 50 fpm. The lack of sensitivity of finish to the cutting fluid used made it evident that this was not a good variable to use for rating water-base cutting fluid performance.

Concluding Remarks

The best way of rating the performance of water-base cutting fluids appears to be in terms of tool-wear characteristics. The recommended procedure involves cutting tests under constant conditions with the exception of cutting speed and cutting fluid. Taylor plots of tool life (in terms of both constant wear land and total destruction) should be prepared and lines of constant F added to these plots. From such graphs it is possible to compute values of the quantity $\left(\frac{1}{V^*(1-n)}\right)$ where V^* is the cost optimum cutting speed and n is the inverse slope of the appropriate Taylor curve. The quantity $\left(\frac{1}{V^*(1-n)}\right)$ has been shown to be directly proportional to the optimum cost per part and hence, represents an ideal measure of the performance of a cutting fluid. Representative results are considered in detail for AISI 4340 steel and the application of the general method to any type of steel is discussed.

It was found that the Taylor plots for constant wear land and total destruction are basically different for relatively freely cutting steels and steels like AISI 4340. The former are shown to involve a wear-land failure, while the latter are shown to fail by cratering.

It is found that, in rating water-base cutting fluids, the cost of the fluid may be ignored, since it is insignificant relative to the machining cost per part.

Good correlation has been found between short-time cooling tests tests (0.001 sec.), and the tool-life characteristics of cutting fluids used at speeds above those where BUE is present, and below those where time for cooling is still available (i.e., in the vicinity of 500 fpm for AISI 4340 steel). However, such a test does not provide a useful picture of cutting-fluid action for the region where lubrication action is important (below 500 fpm).

It does not appear possible to write a single, concise specification for cutting-fluid performance. The relative rating of a group of fluids will depend not only upon tool and workpiece details, but also upon the speed range involved in use.

~~It would appear that use of at least two types of water-base~~ fluids are justified. One is for use at speeds of 500 fpm and above where cooling capacity is of major importance. Such fluids could be specified by reference to a bench-type cooling test such as that described in this report. The second type of fluid is one for use at speeds below 500 fpm. A performance specification for such a fluid could be given as a certain minimum acceptable percentage improvement over dry cutting under standard conditions at a given speed such as 300 fpm.

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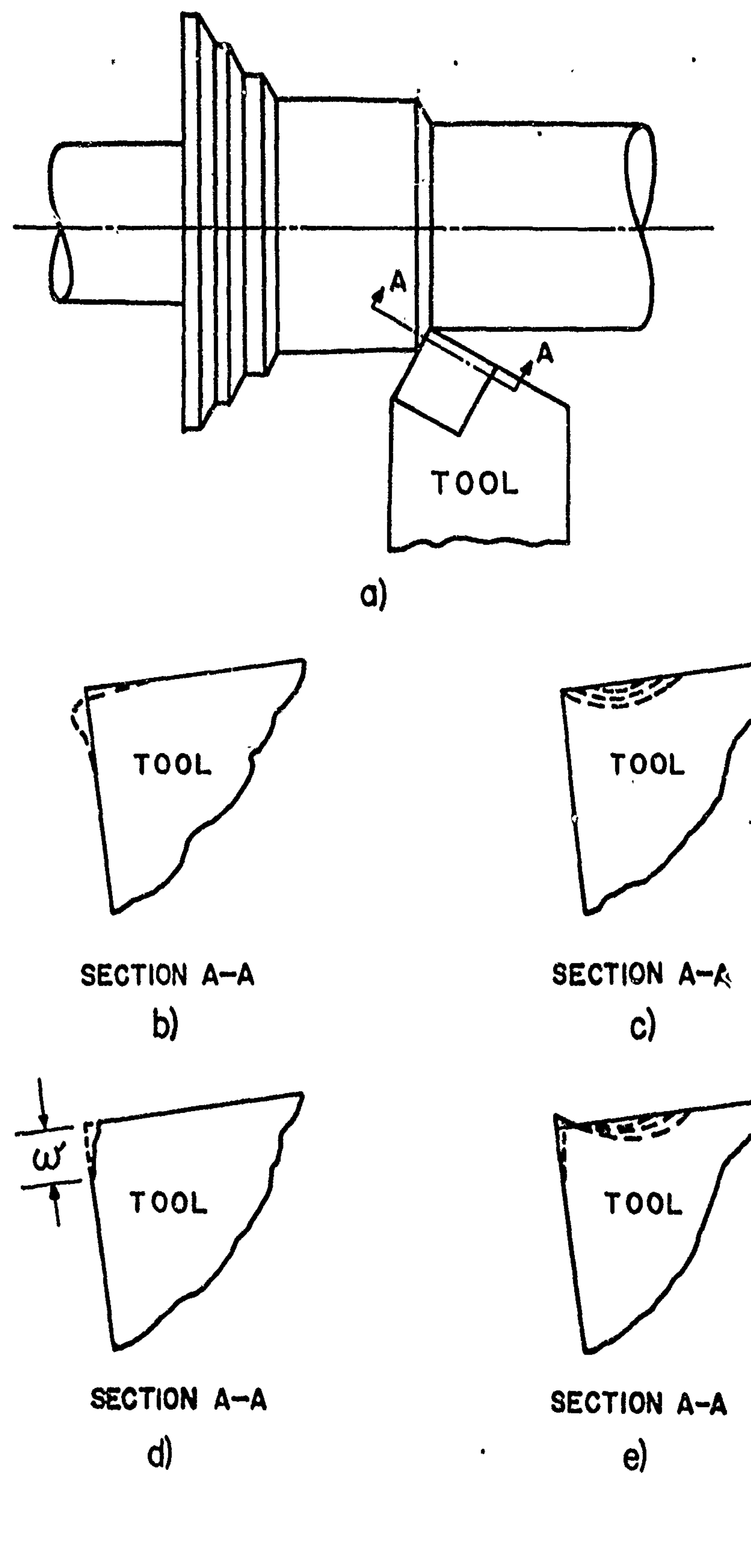

Fig. 1 Changes in tool appearance during use. a) Plan view of tool in operation showing chamfer at end of bar to prevent chipping as tool finishes cut, b) plastic deformation of tool tip, c) formation of crater in absence of built-up edge, d) the wear land (w), e) formation of crater in presence of built-up edge.

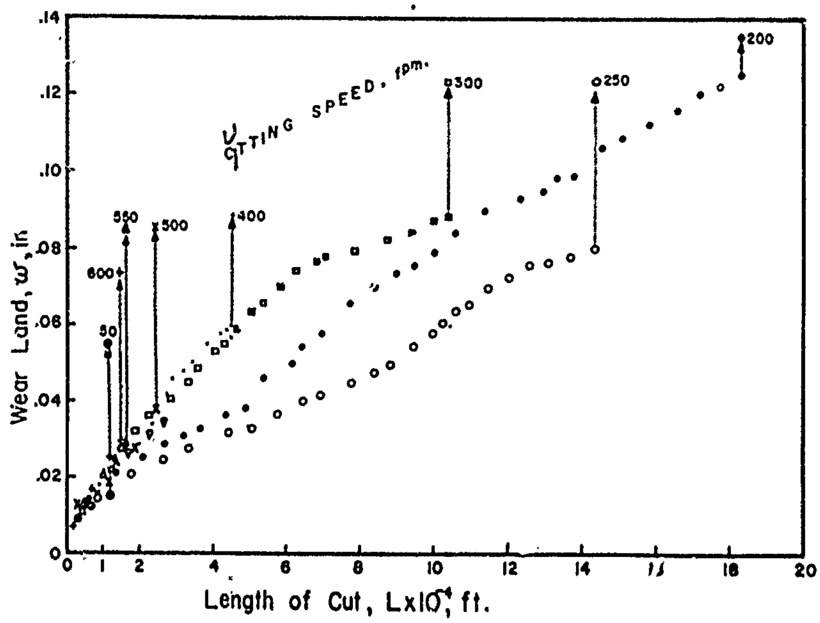

Fig. 2 Wear curves for annealed AISI 4340 steel cut using a carbide tool having the following ASA geometry: -7, -7, 7, 7, 15, 15, 1/32 in. Depth of cut, 0.100 in; feed, 0.0104 ipr; fluid, tap water applied at rate of 1-1/2 gal/min at temperature of 60F.

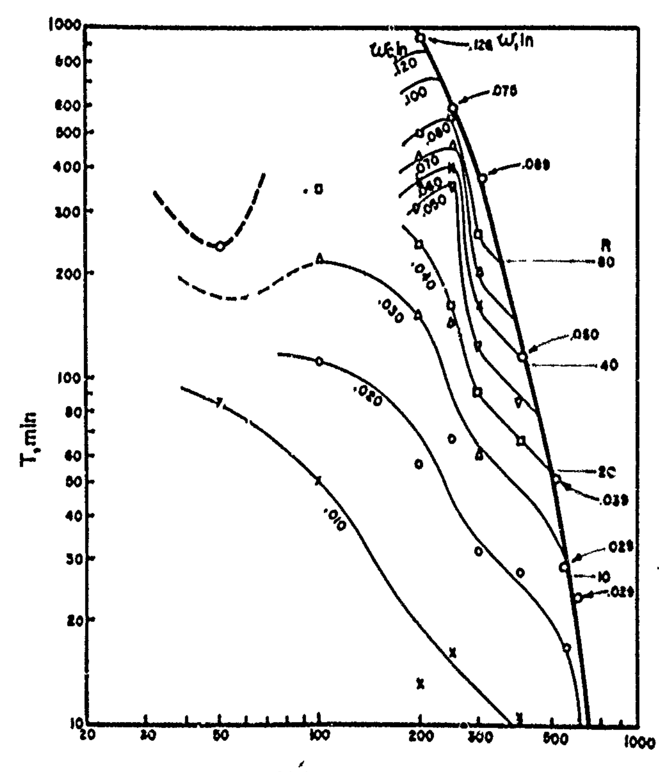

Fig. 3 Tool life-speed curve for data of Fig. 2.

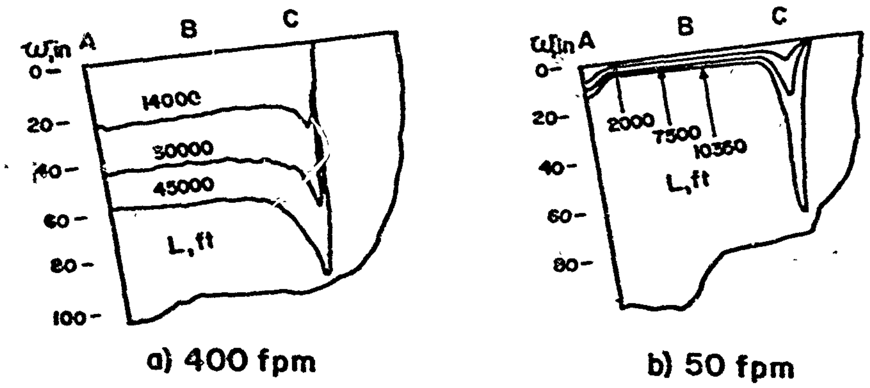

Fig. 4 Wear land patterns obtained in cutting AISI 4340 steel under conditions of Fig. 2.

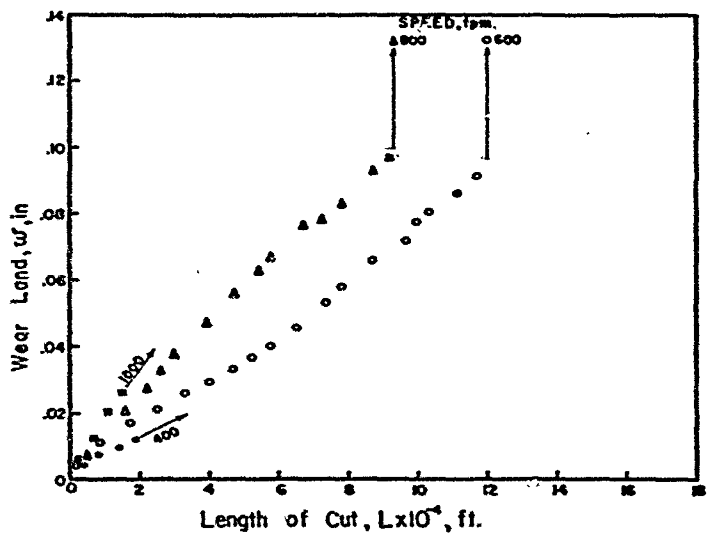

Fig. 5 Wear curves for hot rolled AISI 1020 steel cut using a carbide tool having the following ASA geometry: -7, -7, 7, 7, 15, 15, 1/32 in. Depth of cut, 0.100 in; feed, 0.0104 ipr; fluid tap water applied at rate of 1-1/2 gal/min at temperature of 60F.

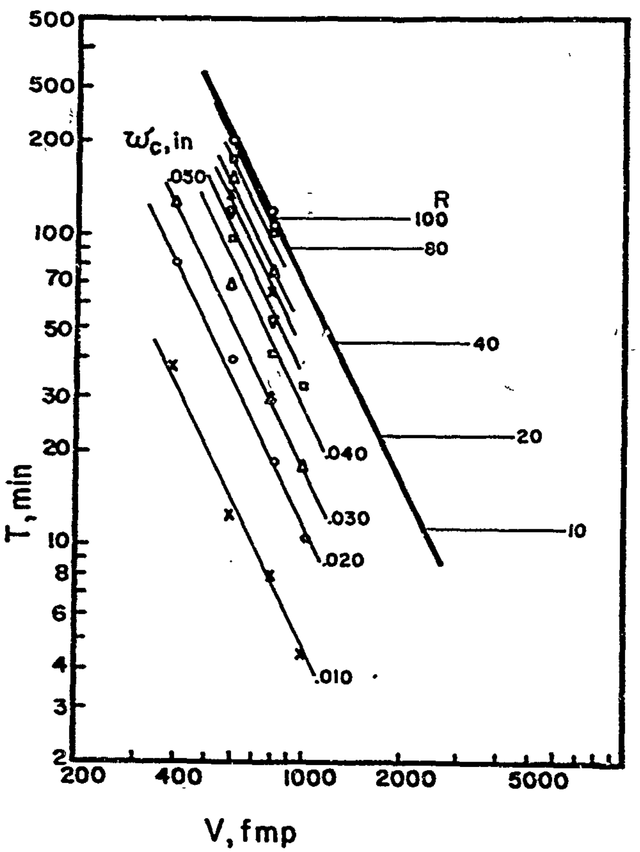

Fig. 6 Tool life-speed curve for data of Fig. 5.

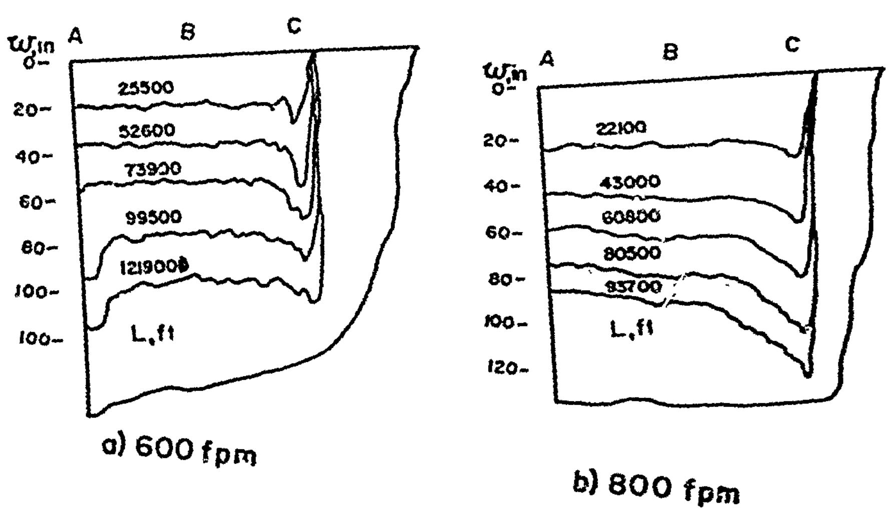

Fig. 7 Wear land patterns obtained in cutting AISI 1020 steel under conditions of Fig. 5.

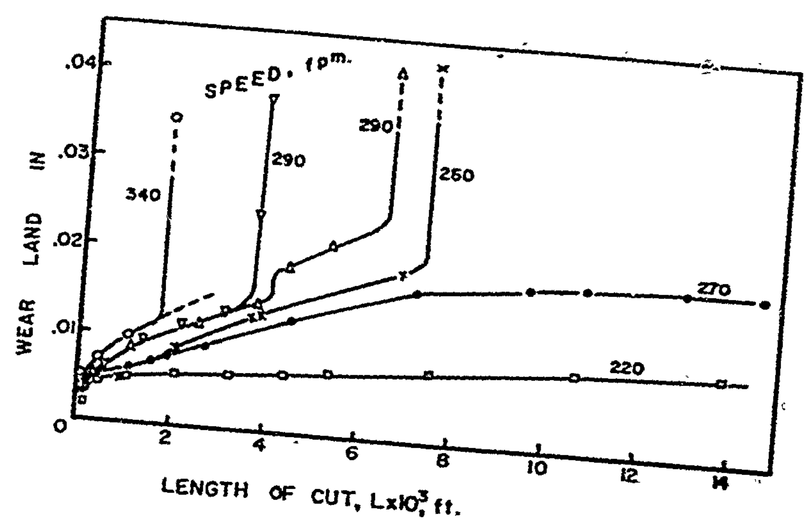

Fig. 8 Wear curves for 18-4-1 HSS tool cutting AISI C1117 steel. ASA geometry: 0, 10, 5, 5, 5, 0, 0.015 in.; feed, 0.0058 ipr; depth of cut, 0.05 in; cutting fluid, none.

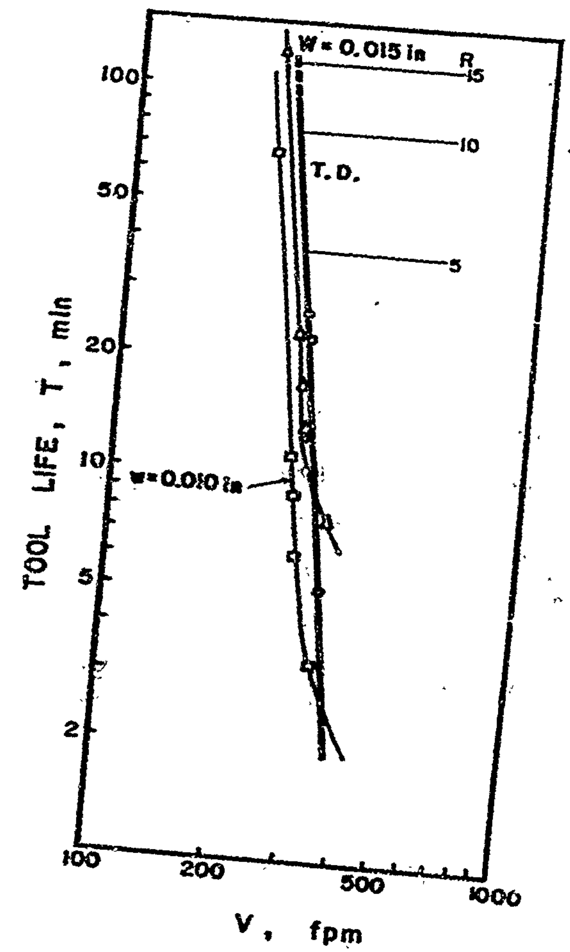

Fig. 9 Tool life-speed curve for data of Fig. 8.

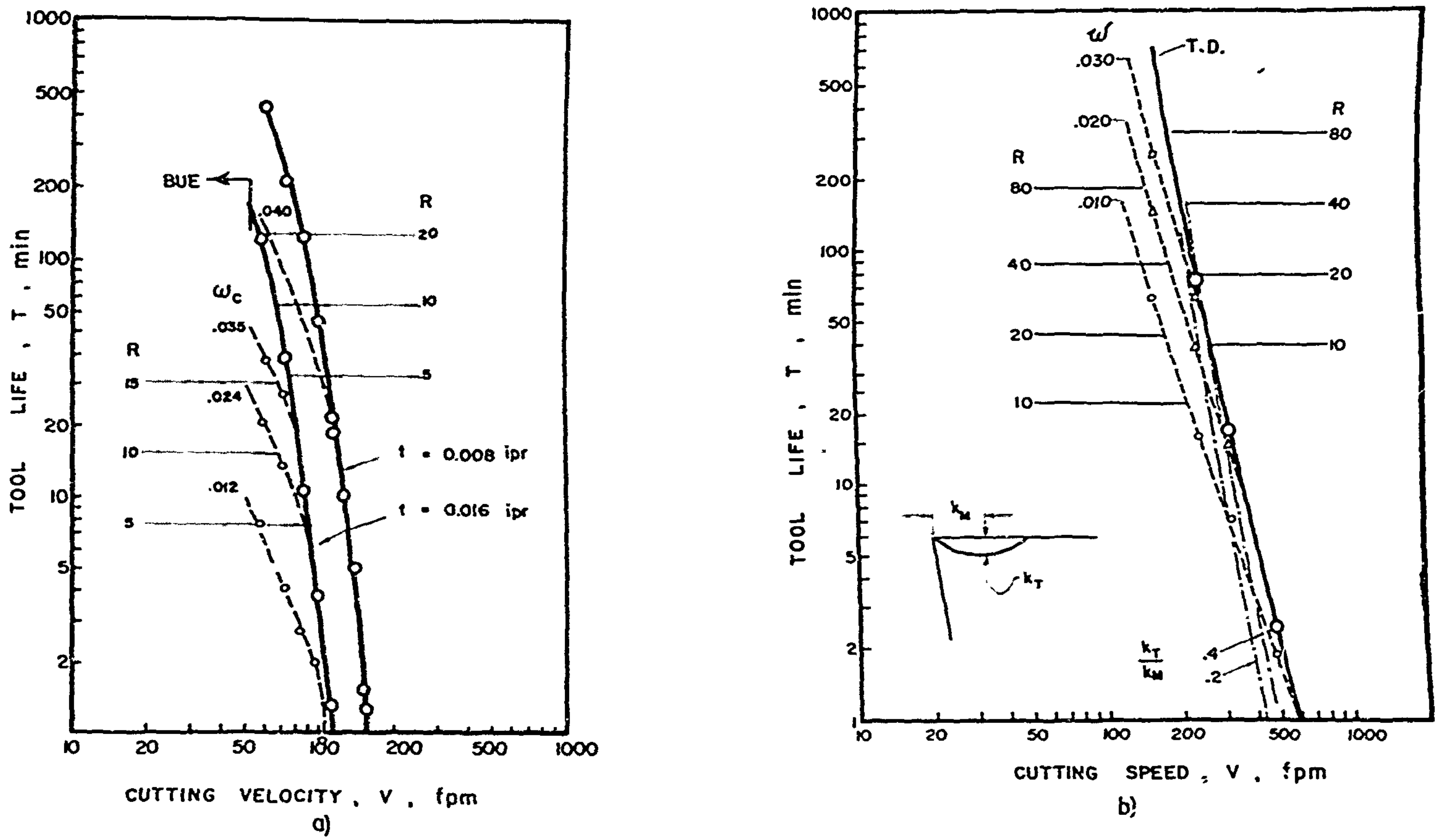

Fig. 10 Tool life-speed curves for German C68 steel of ultimate tensile strength of 82 Kg/mm^2 (107,000 psi). This is an unalloyed steel equivalent to AISI 1068 in the as received condition (after Weber, Ref. 2).

a. 18-4-1 HSS tool with 45° side-cutting-edge angle cutting dry. Depth of cut, 3mm (0.118 in.); feed, 0.2 and 0.4 mm/rev (0.008 and 0.016 ipr).

b. L-3 German carbide tool with 5° normal rake angle, 0° parallel back rake angle, 45° side cutting edge angle, 5° relief angle, and 0.6 mm (0.024 in) nose radius. Depth of cut, 2 mm (0.079 in); feed, 0.56 mm (0.022 ipr); cutting fluid, none.

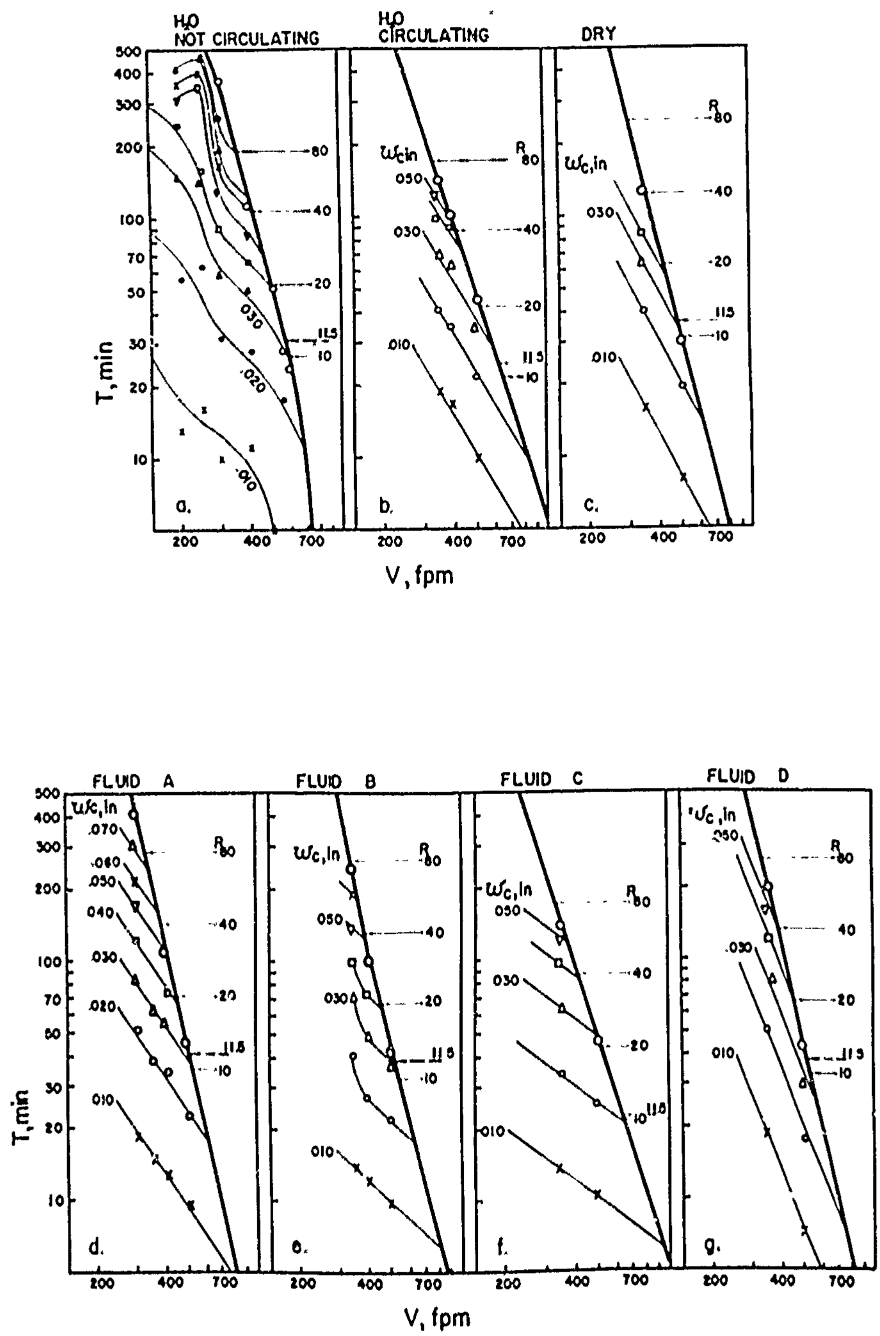

Fig. 11. Tool life-speed curves for different cutting fluids used in machining AISI 4340 steel with a carbide tool with the following ASA geometry: -7, -7, 7, 7, 15, 15, 1/32 in. Depth of cut, 0.100 in.; feed, 0.0104 ipr. Rate of fluid flow, 1-1/2 gal/min.

a. Noncirculating water at 60°F.
b. Circulating water at 90°F.
c. Dry Tool.
d. Cutting fluid A, 2.5% in water.
e. Cutting fluid B, 2.5% in water.
f. Cutting fluid C, 2.5% in water.
g. Cutting fluid D, 2.5% in water.

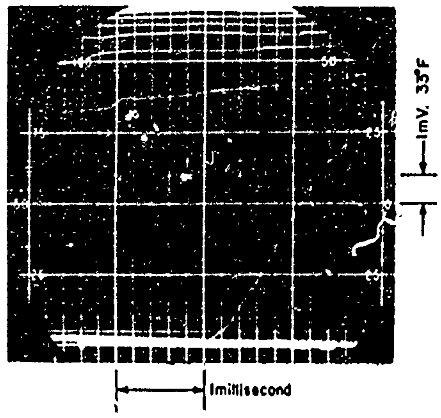

Fig. 12 Cooling trace for stream of water directed upon surface of steel plate heated to 600°F.

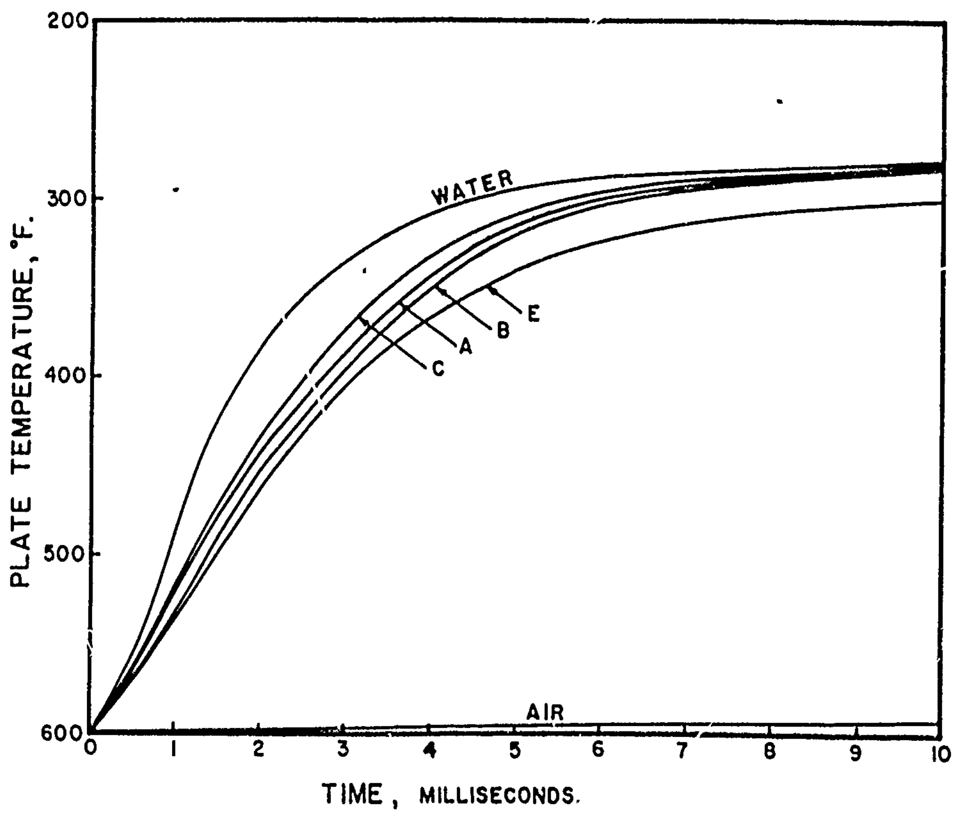

Fig. 13 Cooling curves for different fluid streams directed against steel surface heated to 600°F.

a. Water stream.
b. Stream of fluid A, 2.3% in water.
c. Stream of fluid B, 2.5% in water.
d. Stream of fluid C, 2.5% in water.
e. Stream of fluid E, 2.5% in water.
f. Stream of dry air.